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GEOSPACE PLASMA DYNAMICS

Daniel Ober, et al.

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Final Report

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This final report provides a summary of progress made during FY11 on the Air Force Office of Scientific Research task titled, "Geospace Plasma Dynamics." The goal of this research effort was to develop a detailed knowledge of the space environment by analyzing satellite data and developing the theories needed to explain the observations. In this way we hoped to improve our capability to predict the state of the space environment. This effort included 2 basic research efforts. They were: 1) Investigate solar wind-magnetosphere-ionosphere coupling processes, and 2) Investigate the physics of the low-latitude ionosphere.

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1. INTRODUCTION

This final report provides a summary of progress made during FY11-12 on the AFOSR task titled "Geospace Plasma Dynamics". The goal of this research effort was to develop a detailed knowledge of the space environment by analyzing satellite data and developing the theories needed to explain the observations. In this way we hoped to improve the current capability to predict the state of the space environment. This research effort included 2 basic research efforts. They were 1) Investigate solar wind-magnetosphere-ionosphere coupling processes, and 2) Investigate the physics of the low-latitude ionosphere.

2. BACKGROUND

This research task originally consisted of 4 research areas. They were 1) Investigate the spatial and temporal evolution of the turbulent field-aligned Birkeland current system, 2) Investigate solar wind-magnetosphere-ionosphere coupling processes, 3) Specify and predict long-term (3 day) forecast of the low-latitude ionosphere using first principles models, and 4) Investigate the physics of penetration electric fields. In the last year of the research effort these tasks were narrowed and redefined so that the science goals were more aligned with the needs of the Air Force and that our research efforts were more likely to produce results that support current AFRL applied research efforts. Several publications resulted from this effort.

The subsequent sections present a summary of the activities conducted for this project. In Section 3 we will present the data sets and models used in this task. Section 4 contains a summary of the significant published results of this effort. Concluding remarks are presented in Section 5.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

This research effort included a combination of satellite data analysis and numerical modeling efforts. Satellite data came from The Defense Meteorological Satellite Program (DMSP) and the Communication/Navigation Outage Forecasting System (C/NOFS) satellite.

DMSP is a group of polar orbiting spacecraft assigned to monitor meteorological, oceanographic, and solar-terrestrial environments. Each DMSP satellite has a ~101 minute, near-polar 98.9 degree inclination orbit at an altitude of ~850 km. Orbit planes precess 360 degrees per year and thus are fixed in local time typically near either the 0600-1800 LT or 0900-2100 LT plane. Because of the Earth's offset dipole axis the DMSP spacecraft sample a wide range of magnetic local times at polar latitudes. The principal space environment sensors include the auroral particle spectrometer (SSJ), the fluxgate magnetometer (SSM), and the Topside, Thermal Plasma

Monitor (SSIES) instruments. Data from these instruments are widely utilized to study a wide range of auroral and low-latitude processes.

C/NOFS [1] was launched in April 2008. Its scientific objectives are to understand the physical processes that lead to the formation of plasma bubbles and plumes in the nighttime equatorial ionosphere. C/NOFS is a low-inclination (±13^{o} in geographic latitude) satellite, with 70 an orbital period of ~100 min. The apogee and perigee of C/NOFS are 850 and 400 km, respectively.

In addition to satellite data, the Integrated Space Weather Model (ISM) [2] was used to study solar wind-magnetosphere-ionosphere coupling processes. ISM uses standard MHD equations augmented with hydrodynamic equations for the collisionally-coupled neutral thermosphere. The code transitions seamlessly from pure MHD in the solar wind and magnetosphere to equations appropriate for the ionosphere and thermosphere at low-altitudes. ISM equations are solved within a three-dimensional computational domain extending upward from an interior spherical boundary at the bottom of the E-layer (100 km) through the magnetosphere and into the solar wind. The spatial resolution of ISM's computational grid varies from a few hundred kilometers in the ionosphere to several R_E in the distant magnetotail downstream from Earth.

4. RESULTS AND DISCUSSION

The electric fields/plasma drifts are believed to be the primary driver of the dynamics in the low-latitude ionosphere. In [3] we describe and demonstrate the capabilities of the low-latitude physics-based ionospheric model (PBMOD) developed at the Air Force Research Laboratory (AFRL) to specify radio scintillations using data collected during an April 2009 campaign dedicated to measurements with Communication/Navigation Outage Forecasting System (C/NOFS). With electric field measurements from the Vector Electric Field Instrument (VEFI) ingested into PBMOD, estimated scintillation strengths (S4) were comparable with ground measurements at 250MHz recorded at Ancón, Peru; Christmas Island; and Kwajalein Atoll. In general, the estimated scintillation regions from PBMOD are associated with observed density perturbations. Incoherent scatter returns on the ARPA Long-Range Tracking and Identification Radar (ALTAIR) on Kwajalein Atoll during the April 2009 campaign also demonstrated density perturbations at the bottom layer of F region during the same period. We found these scintillation regions to be associated with upward drifts confirming the Rayleigh-Taylor instability theory that the nightside ionosphere is unstable due to eastward electric fields (i.e., upward plasma drifts). Although spurious data gaps prevent us from precisely determining the physical conditions, the C/NOFS mission allows us to directly ingest electric field measurements into the model to study ionospheric irregularities for the first time.

In [4] *in situ* ion density fluctuation measurements are compared with corresponding field-line-integrated depletions as inferred from electric field measurements. Results indicated that local measurements of the normalized density depletion near the magnetic equator may be far less than other points on the same field line. With confirmation from 3D bubble simulations, the

distribution of the normalized density depletion is a weighted distribution concentrated at the latitudes of the Appleton anomalies (i.e., ~± 15^{o} off the magnetic equator) and becomes more heavily weighted when the field-aligned bubbles rise to the peak of the anomalies. An implication is that the local measurements of the density depletions cannot be trivially extended to higher latitudes in an effort to calculate scintillation at these latitudes. We propose an estimation of the density depletion of whole field lines from local zonal electric field perturbations.

High-speed solar wind streams cause recurrent geomagnetic activity and ionospheric disturbances. In [5], we analyze the equatorial ionospheric ion drift measured by the Defense Meteorological Satellite Program (DMSP) satellites near dusk when high-speed solar wind streams with a period of 13.5 days occurred during January–April 2007. A well-defined quantitative correlation between the solar wind velocity and the equatorial ionospheric ion drift is identified for the first time. The plasma drift in the dusk equatorial ionosphere induced by high-speed solar wind streams is eastward in the zonal direction and downward in the vertical direction at the altitude of DMSP orbit (□840 km) during this low solar activity period (January–April 2007). The zonal component of the equatorial ionospheric ion drift is inversely correlated with the vertical component. The ionospheric ion zonal drift varies, on average, from -40 to 40 m s^{-1} when the solar wind velocity varies from 300 to 700 km s^{-1} over a 13.5 day period, and the ion vertical drift varies from 10 to -10 m s^{-1}. The quantitative correlations between the solar wind velocity and ionospheric ion drift and between the vertical and zonal components of the ion drift velocity are important for understanding the equatorial ionospheric electrodynamics associated with high-speed solar wind streams and for space weather prediction.

In [6] we present the observations of equatorial plasma bubbles in the evening sector by the Communication/Navigation Outage Forecasting System (C/NOFS) satellite during 2011. We illustrate with a few examples the overall properties of the equatorial ionosphere as the solar activity approached maximum. C/NOFS was often below the F peak and this allowed us to examine the early phases of irregularity formation. We show examples when C/NOFS detected a continuous generation of plasma bubbles near the sunset terminator over eight successive orbits (~12 hours). A clear pre-reversal enhancement of upward plasma drift occurred between 18:00 and 19:00 LT when plasma bubbles were detected by C/NOFS, and the peak value of the upward ion drift at or near the magnetic equator was 40-70 m s-1. In some cases, C/NOFS was well below the F peak and detected wide regions with very low plasma density over ~3000 km in longitude in the evening sector, and plasma bubbles were generated within the low-density region. C/NOFS also detected simultaneous existence of plasma bubbles between 19:00 and 03:00 LT, corresponding to a longitudinal coverage of ~12,000 km. Significant differences in the characteristics of plasma bubbles between periods of low and high solar activity are identified. Large plasma bubbles occur in the midnight-dawn sector at low solar activity but in the evening sector at high solar activity. The lifetime of plasma bubbles is long (7 hours or longer) at low solar activity but is short (~3 hours) at high solar activity. Broad plasma depletions occur near dawn at low solar activity, but wide low-density regions with multiple plasma bubbles occur in the evening sector at high solar activity.

Large-scale periodic plasma bubbles are often observed by ionospheric radars and satellites. The seeding effect of atmospheric gravity waves has been widely used to explain the generation of

the periodic plasma bubbles. However, it has not been well understood where the seeding process occurs and whether multiple plasma bubbles are simultaneously seeded by gravity waves over a large longitudinal range. In [7], we present the observations of equatorial plasma bubbles by the Communication/Navigation Outage Forecasting System (C/NOFS) satellite. It was found that quasi-periodic plasma bubbles occurred in the post-midnight sector, with nearly equal distance of 800-1000 km between successive bubbles, in 2008 under deep solar minimum conditions. The bubble chain covered a longitudinal range of ~7000 km between 00:00 and 04:00 LT. Quasi-periodic plasma bubbles were measured by C/NOFS in the evening sector in 2011 during the ascending phase of the solar activity, and the longitudinal distance between successive bubbles was ~500 km. We propose a new causal mechanism to explain the generation of quasi-periodic plasma bubbles. In this scenario, atmospheric gravity waves are generated near the sunset terminator and initiate the Rayleigh-Taylor instability there. The spatial (longitudinal) periodicity of plasma bubbles is determined by the temporal periodicity of the seeding gravity waves. A period of 15-30 min of the seeding gravity waves corresponds to a longitudinal separation of 500-1000 km between successive bubbles. This new mechanism provides a reasonable explanation of the observed quasi-periodic plasma bubbles.

Solar wind dynamic pressure has been shown in recent studies to be a significant driver of ionospheric convection and global auroral changes. Specifically, sudden enhancements of the dynamic pressure may significantly reduce the size of the polar cap and the amount of open flux, enhance auroral precipitation and the width of the oval at all magnetic local times (MLT), and increase the transpolar potential and ionospheric convection. These effects are particularly pronounced when the compression occurs under southward IMF conditions. In [8] we investigate the effect of dynamic pressure enhancements by comparing global MHD modeling results from the OpenGGCM model with observations from DMSP, FAST, and the Polar UVI instrument. We specifically focus our attention on the effects on the auroral oval, polar cap size, transpolar potential and auroral particle precipitation. We find that when IMF Bz is steady the model reproduces well the direction and timing of the change of the open flux and the cross polar cap potential (CPCP) after the compression. The motion of the separatrix is not reproduced well at specific local times. Long lasting pressure enhancements produce a transient CPCP increase in the observations that declines after about 1-2 hrs. The model reproduces this transient response but it declines at a slower rate and indicates dayside reconnection as the physical source of that enhancement, in contrast to observations which seem to indicate that nightside reconnection is the likely source. The electric potential and particle precipitation observed along the DMSP and FAST orbits are reasonably well reproduced.

Compared to the dayside, dynamics on the flanks of the magnetopause are poorly understood. To help bridge this knowledge gap, in [9] we analyzed Cluster plasma and field measurements acquired during a 90-min period on 20 November 2003 when Cluster crossed the magnetopause four times in the vicinity of the sash. MHD simulations provide a context for Cluster observations. Crossings were between the magnetosheath and an S-shaped plasma sheet, rather than to the open-field lobes of the magnetotail. Cluster encountered two regions of MHD-breaking differences between perpendicular ion velocities and $E \times B$ convection. Ion adiabatic expansion parameter (δi) calculations show that ion gyrotropy was not broken during an episode of strong Alfvén wave activity in the magnetosheath. However, gyrotropy was broken ($\delta i > 1$) during the fourth magnetopause crossing. In the magnetosheath, ion guiding-center motion was

maintained but inertial effects associated with temporally varying electric fields are probable sources of velocity differences. Regarding the magnetopause crossing, the generalized Ohm's law limits possible sources for breaking ion gyrotropy to inertial forces and/or electron pressure gradients associated with a nearby reconnection event. We suggest that Cluster witnessed effects of a temporally varying and spatially limited, flow-through reconnection event between open mantle field lines from the two polar caps adding new closed flux to the LLBL at the sash. Future modeling of flank dynamics must consider inertial forces as significant drivers at the magnetopause and in the adjacent magnetosheath.

5. CONCLUSIONS

The goal of this research effort was to develop a detailed knowledge of the space environment by analyzing satellite data and developing the theories needed to explain the observations. In this way we hoped to improve the current capability to predict the state of the space environment. This research effort included 2 basic research efforts including 1) Investigate solar wind-magnetosphere-ionosphere coupling processes, and 2) Investigate the physics of the low-latitude ionosphere. In this report we summarized the results of 7 publications supported by this research effort.

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